Electric Vehicle Power Electronics

Presented by
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About the Presenter

- Mahesh Krishnamurthy is the Director of the Grainger Power Electronics & Motor Drives Lab at IIT
- Distinguished lecturer with IEEE- Vehicular Technology Society
- Extensive background in Design and Implementation of powertrains in HEVs, PHEVs and EVs
- General Chair, 2014 IEEE Transportation Electrification Conference & Expo
- Advisor for Formula SAE Race Team at IIT

Outline

- Intro to EV Power Electronics – Components, Topologies, Performance requirements
- Intro to Cooling systems in EVs
- Emerging technologies – Wide Band Gap Materials
- R&D and Commercialization Challenges for EV Power Electronics

Classification of Hybrid Vehicles

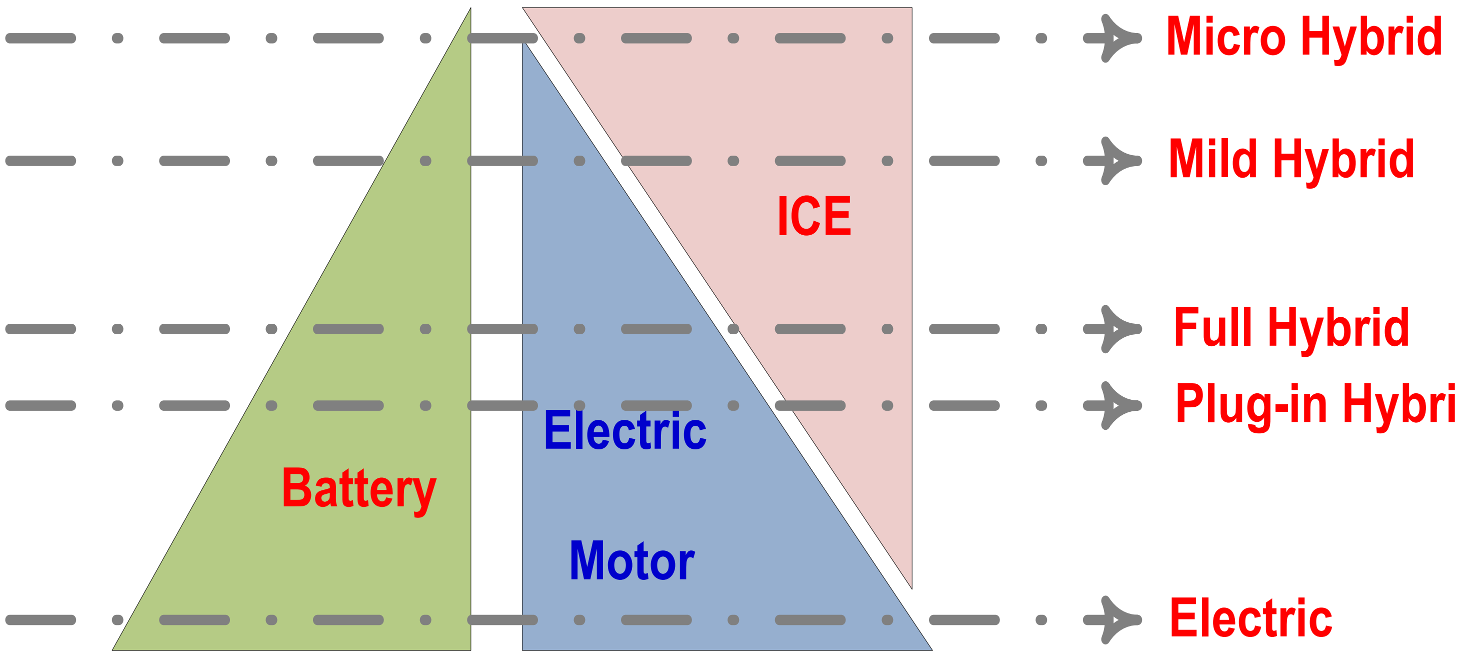

Figure: Classification of hybrid vehicle based on degree of hybridization

Series Hybrid Electric Vehicle

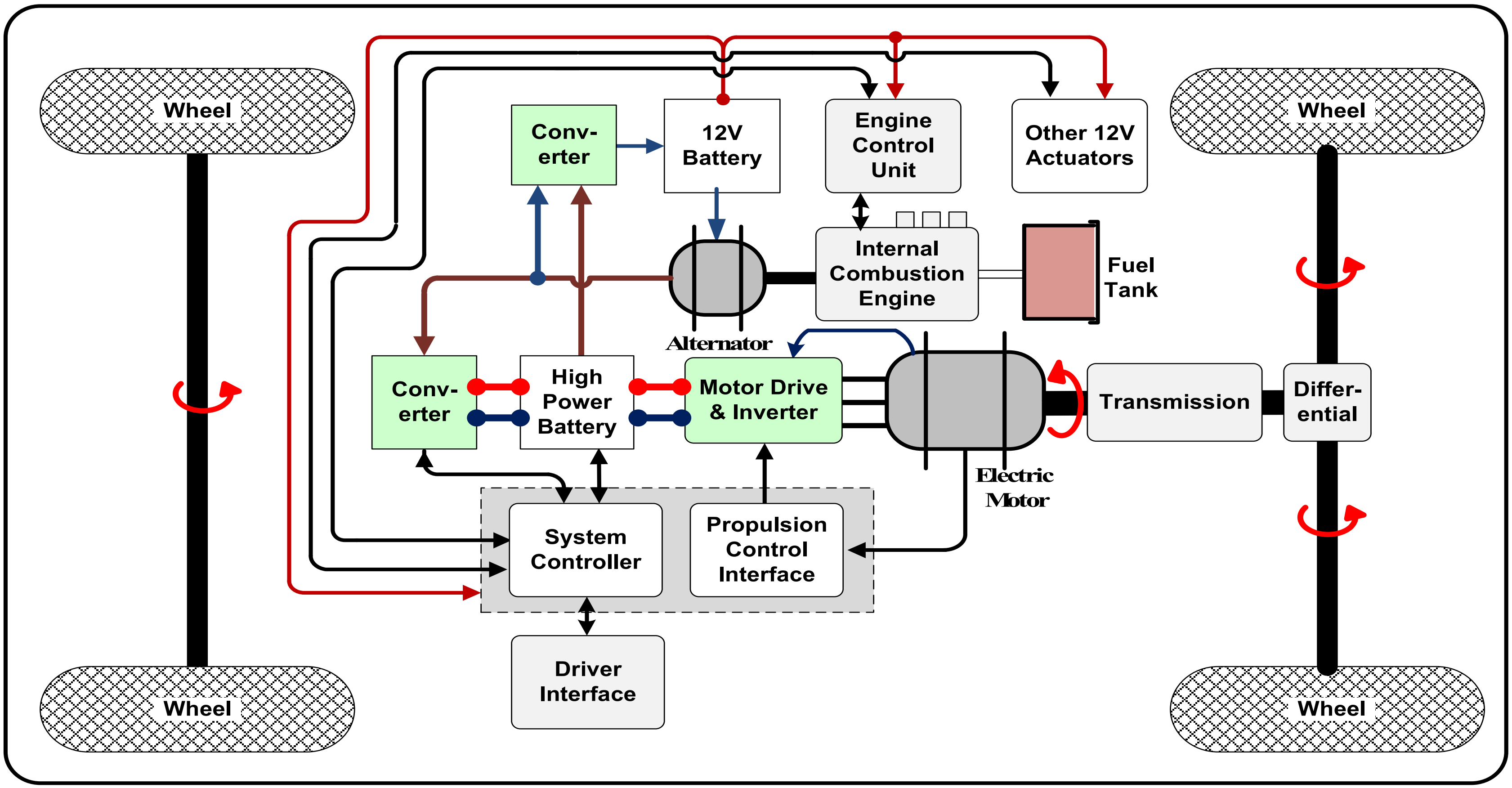

Figure: Typical arrangement of a Series Hybrid Electric Vehicle Propulsion System

Parallel Hybrid Electric Vehicle

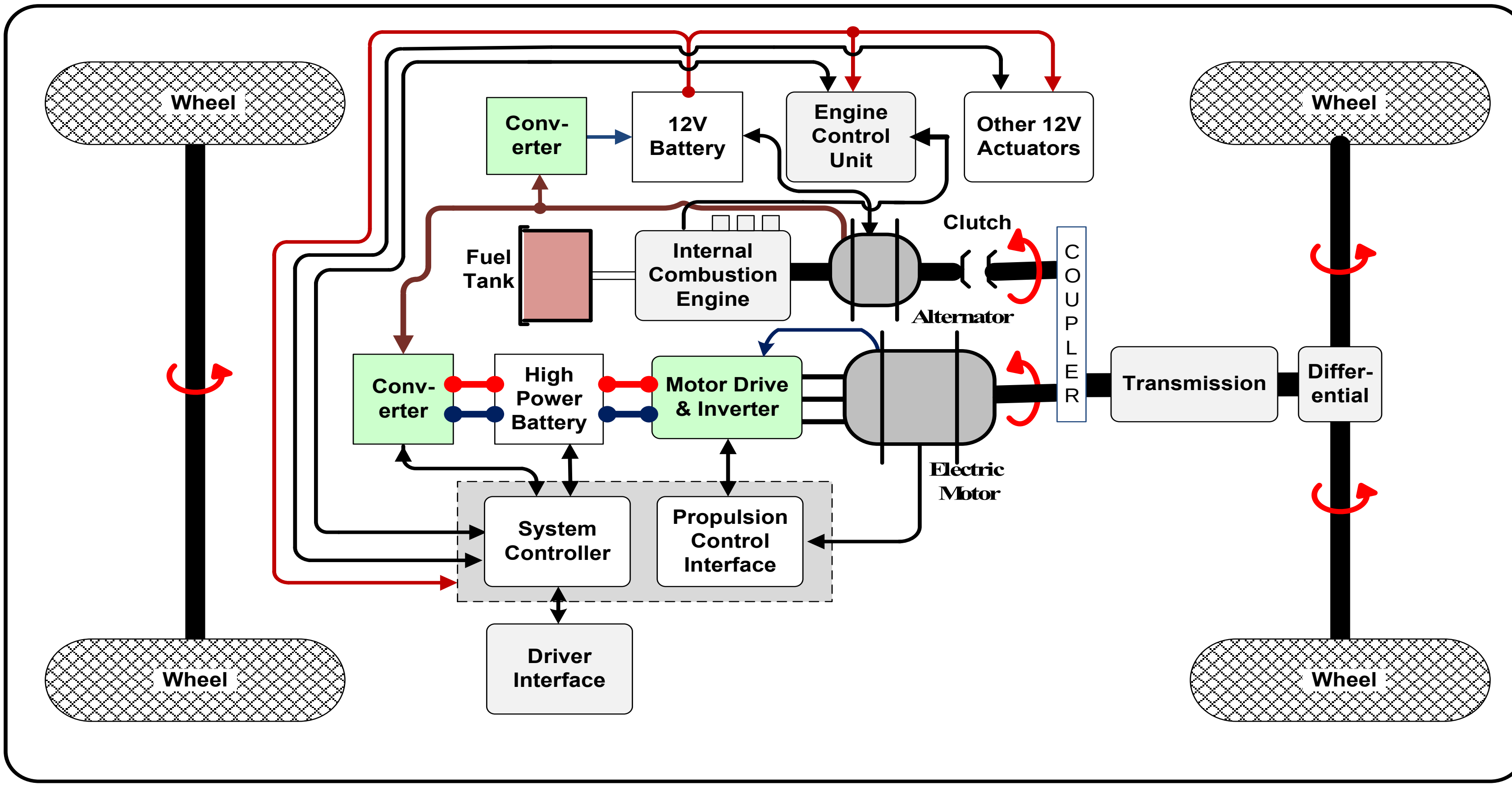

Figure: Typical arrangement of a Parallel Hybrid Electric Vehicle Propulsion System

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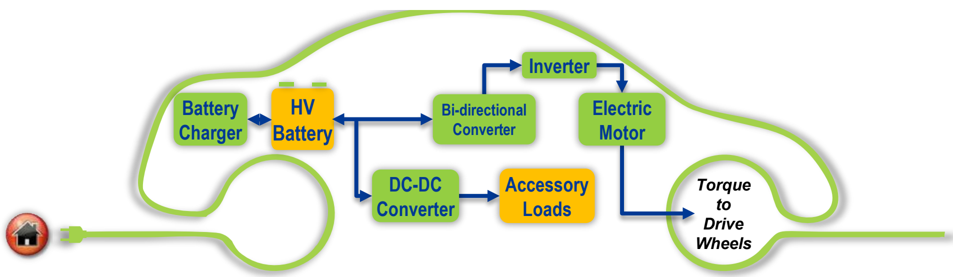
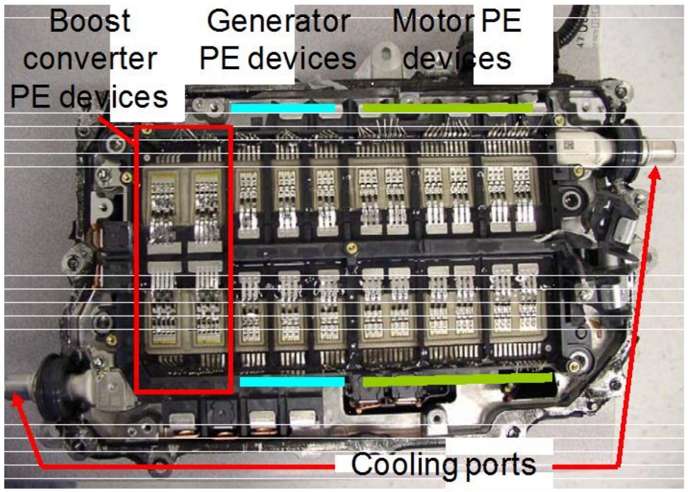
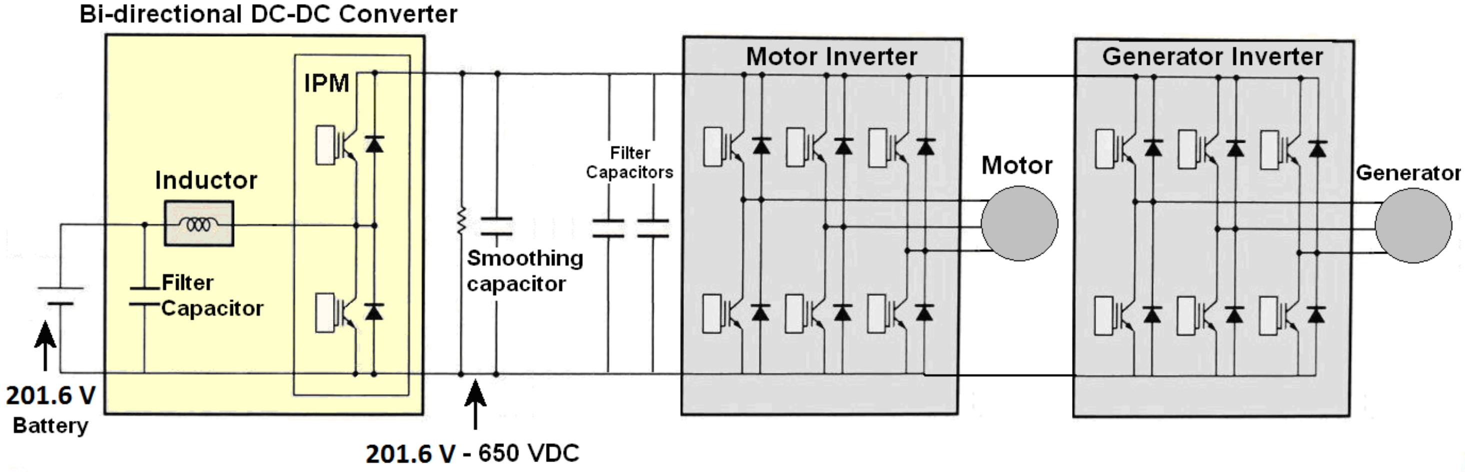
Power Electronics in HEVs and EVs







Ref: Mitch Olszewski, Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System

Introduction to EV Power Electronics – Components, Topologies and Performance Requirements

Switching Devices

Switches
- Uncontrollable
- Controllable
  - Full Controllable
  - Half Controllable
    - Voltage-Control Devices
    - Current-Control Devices

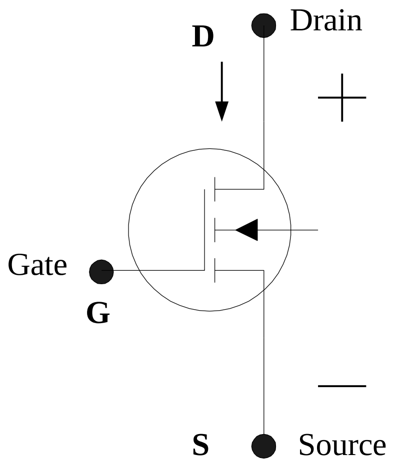
Ideal Switches
- ON State: Short Circuit
- OFF State: Open Circuit

Power Semiconductor Devices

- Power Diode
- Thyristor
- Diac & Triac
- Gate Turn-Off (GTO) Thyristors
- Power Bipolar Junction Transistor (Power BJT)
- Power MOSFET
- Insulated Gate Bipolar Transistor (IGBT)
- MOS Controlled Thyristor (MCT)
- Integrated Gate Commutated Thyristor (IGCT)

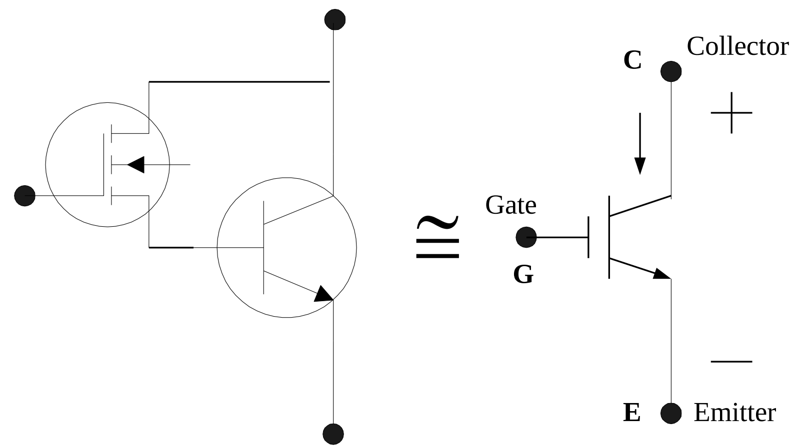
Power MOSFETs

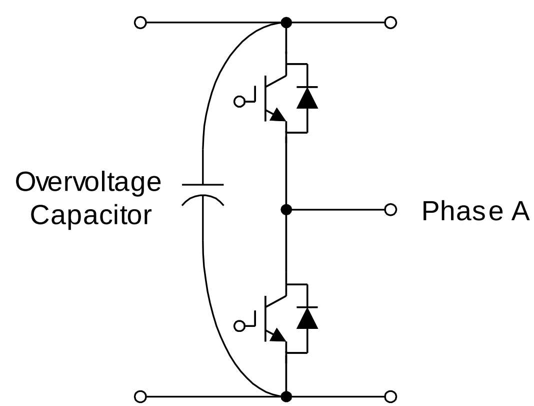
- Voltage-controlled devices.
- Usually N-channel and of the enhancement type.
- When ON, there is a small resistance, i.e., less than 1, between drain and source
- When it is OFF, there is a large resistance (almost open circuit) between drain and source.



Insulated Gate Bipolar Junction Transistor (IGBT)

- Equivalent to power BJTs with bases are driven by MOSFETs.
- Similar to a MOSFET, have high impedance gate, which requires only a small amount of energy to switch the device.
- Similar to power BJT, has a small on-state voltage.





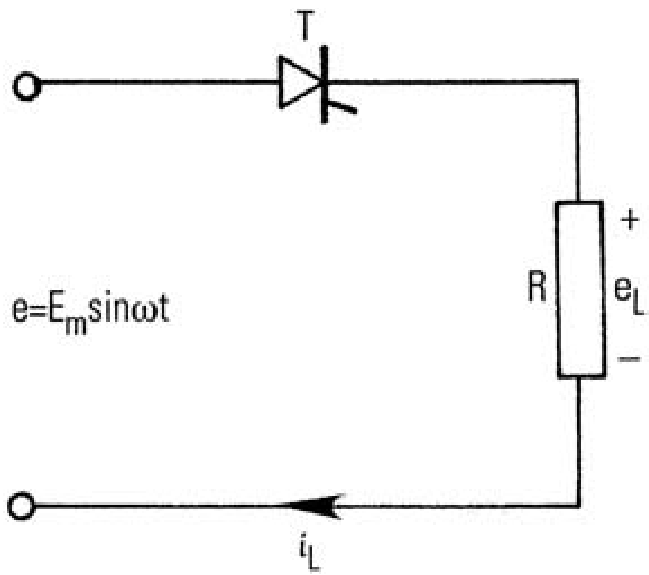
Converters: Rectifier

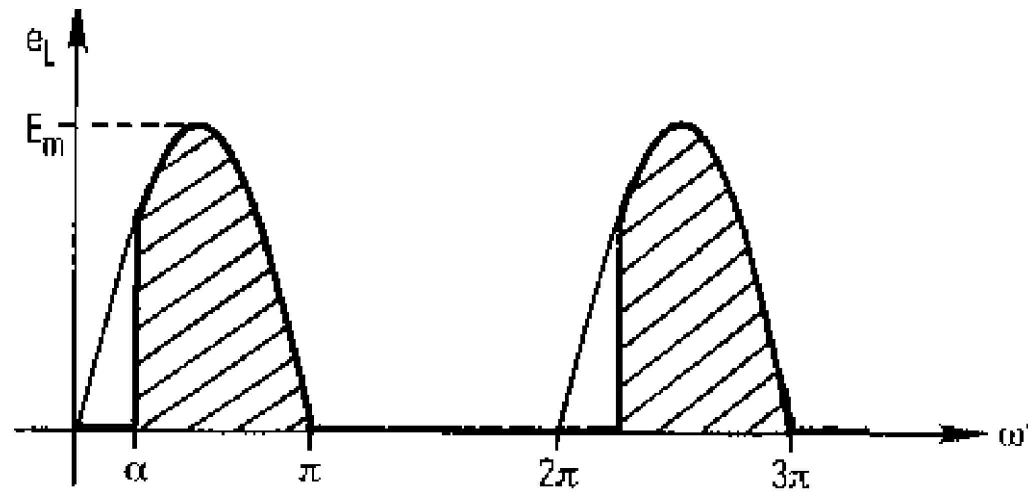
- AC/DC converters employing thyristors with phase control and line commutation have been used widely to convert AC to DC power for applications like DC drives, electrochemical processes, etc.

- In order to alleviate the problems of low frequency harmonics generated by the line commutated converters, PWM type converters are being used in several applications.

- PWM rectifiers have an advantage that the input line side power factor can be set at desired value (leading, unity power factor, or lagging)

Single Phase Half Wave Controlled Rectifier

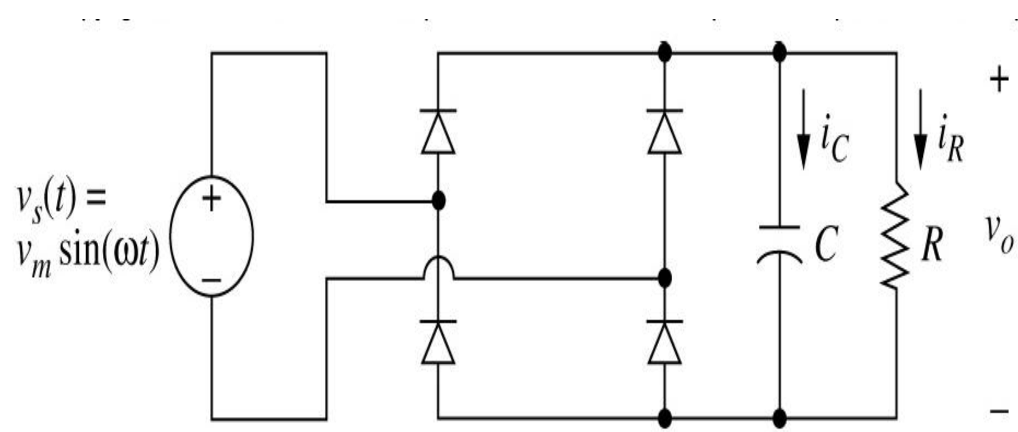


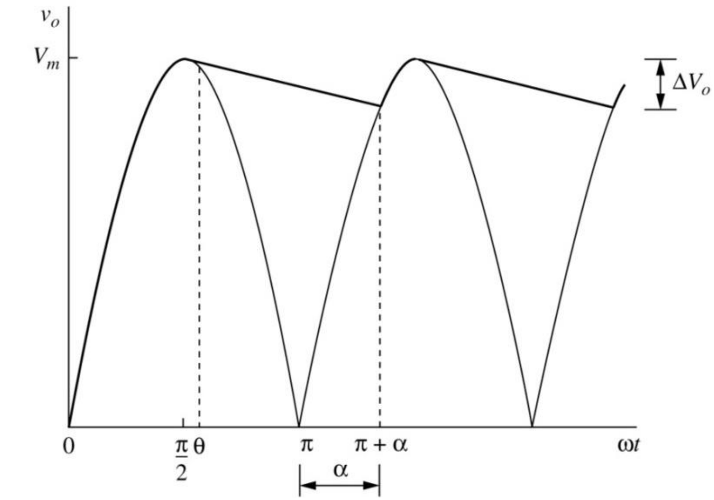


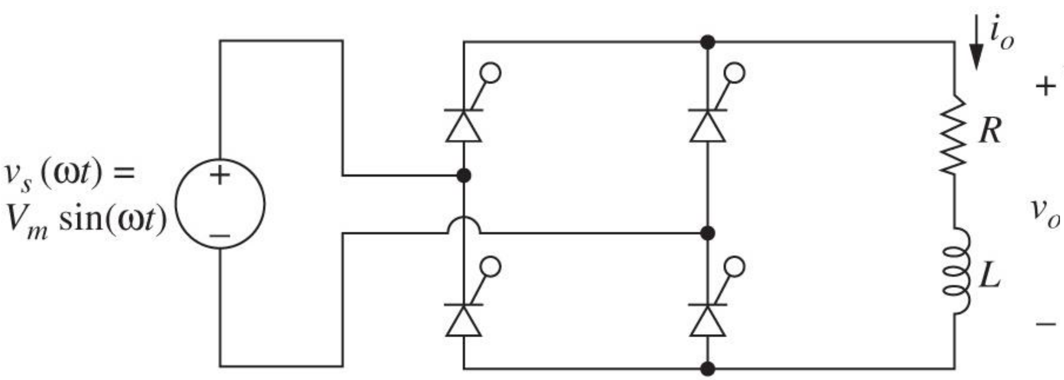
$$E_{av} = \frac{1}{2\pi}\int_{\alpha}^{\pi} e_L(\omega t)\, d\omega t$$

$$= \frac{E_m}{2\pi}(1+\cos\alpha)$$

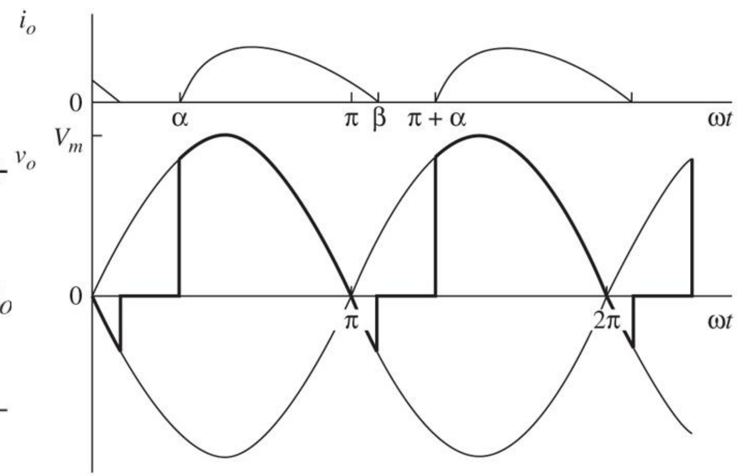
Bridge Rectifier



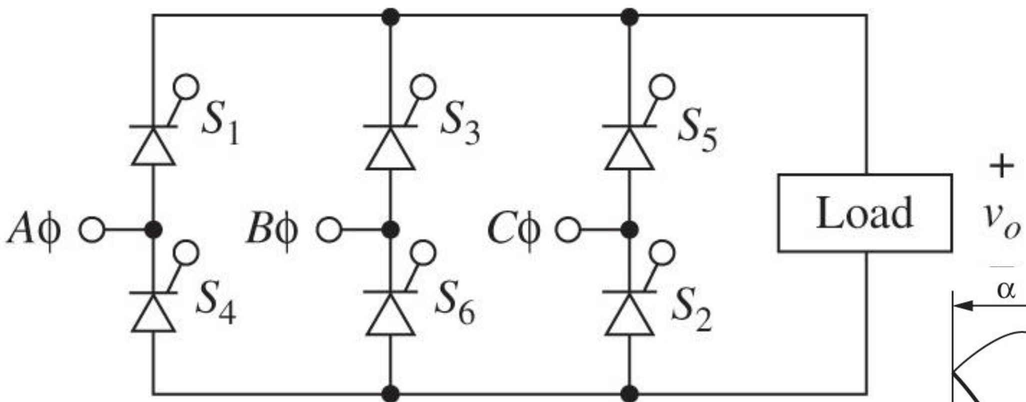




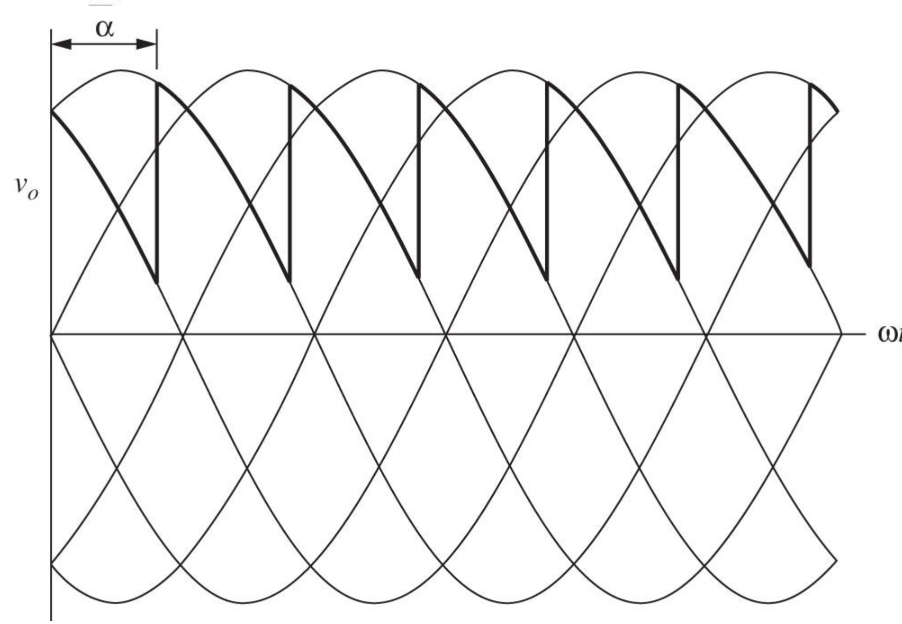
(a)



Three Phase Controlled Rectifier



A three phase bridge can also act as an inverter if the load has a voltage source (such as a generator)



Converters: Chopper

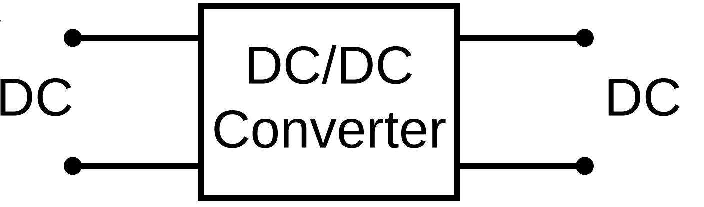
- Converts unregulated DC to regulated DC and widely used in DC motor drives

- PWM choppers like Buck, Boost, Buck-Boost and Cuk

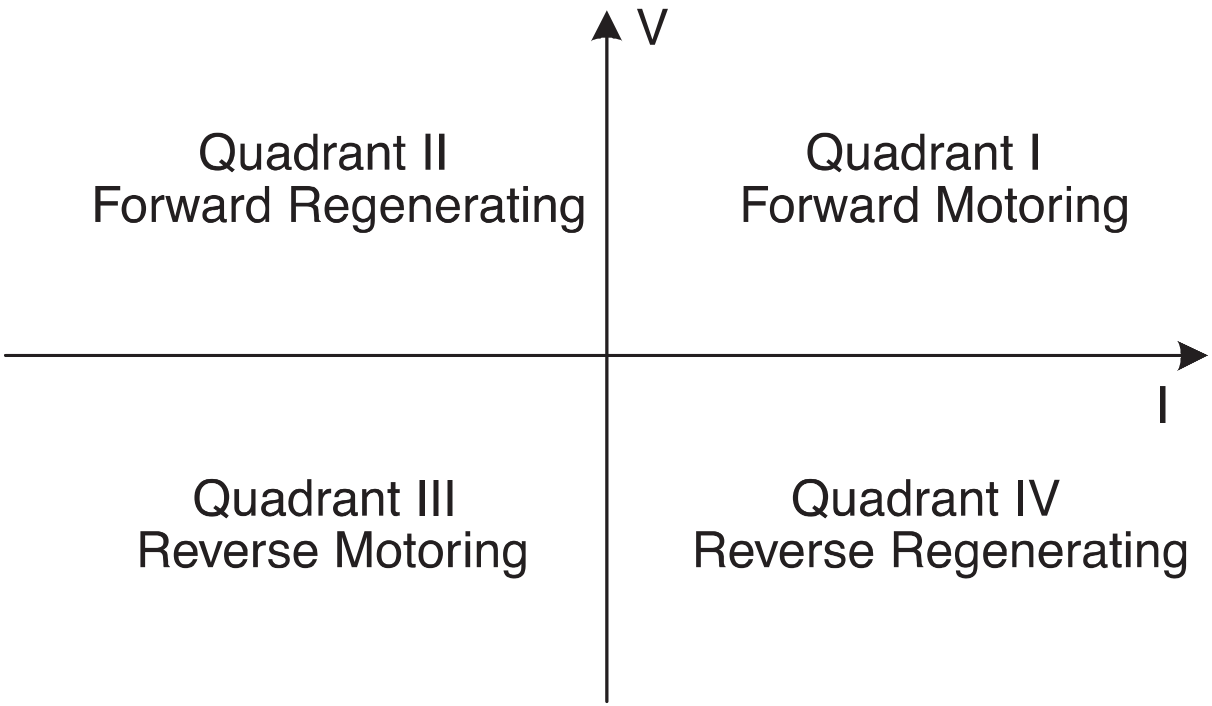
- PWM techniques with hard-switching are typically very lossy

- One alternative is to use resonant and quasi-resonant converters using which the switching frequency can be in the order of few MHz

- Another alternative is to use resonant link converter in which the DC power is first converted to high frequency AC and then rectified using a diode rectifier and a low-pass filter



DC/DC Converters



DC/DC Converters in EVs

- Current EV or PHEV typically have two DC/DC converters on board, connected to the same high voltage DC bus.
- The first one, with a higher rated power (27 kW for the Toyota Prius 2010, 36.5 kW for the Lexus LS 600h, or even higher is the vehicle is a Plug-in Electric Vehicle with fast charging capability) is a bidirectional buck/boost converter and connects the battery pack with the high voltage DC bus (650V for the Toyota Prius 2010).
- It is capable of transferring energy in both directions to allow battery charging (during regenerative breaking) and electric driving mode (wheels powered by the electric motor).
- The devices used for this application are various IGBTs in parallel for each position, with freewheeling diodes, also various chips in parallel [1].

[1] Mitch Olszewski, "FY2011: Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System". Oak Ridge National Laboratory.

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DC/DC Converters in EVs

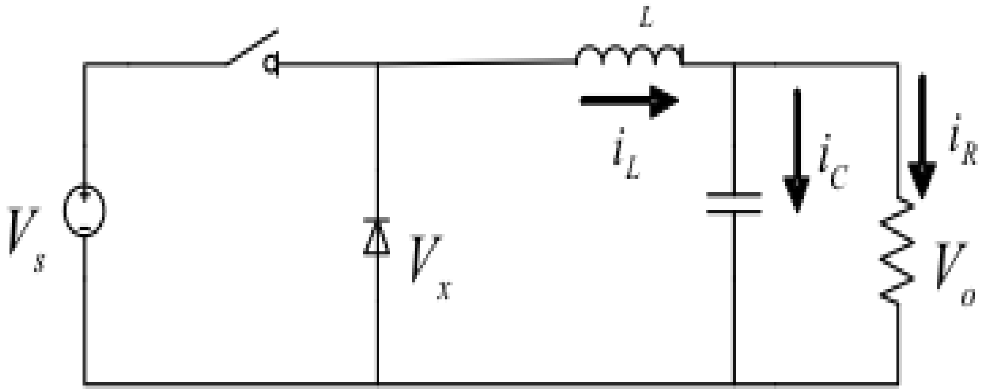
- The second DC/DC converter is usually a one-way converter with isolation (for safety reasons), since it is meant to supply power to the on board DC load such as 12V outlets, lamps, actuators, control computers, etc.

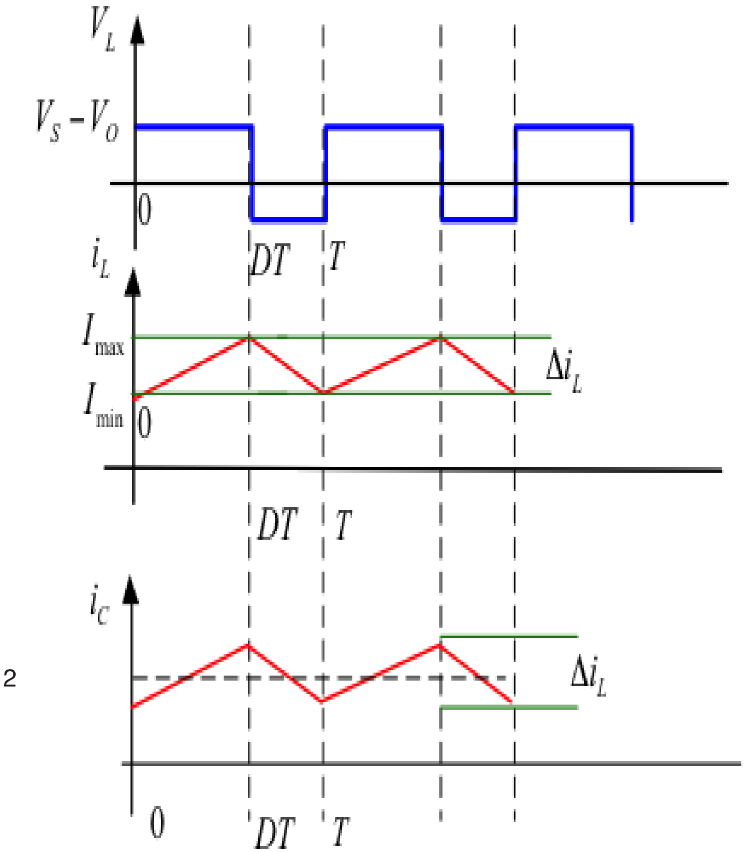
- The introduction of this converter to the architecture of EVs allowed the elimination of the 14V auxiliary battery and the alternator.

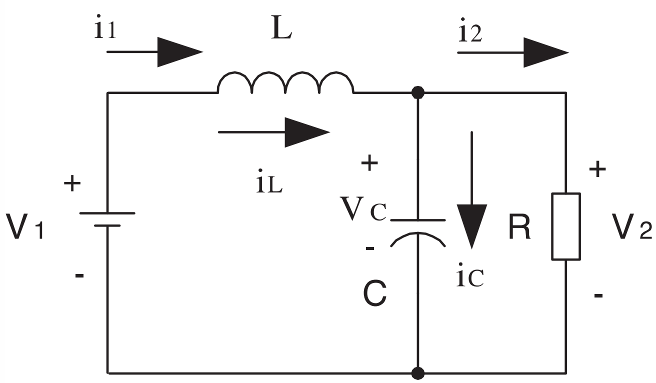
- In the Toyota Prius 2003, the rated power is 1.4 kW and the devices used are commercial power MOSFETs.

- Apart from these two converters there are other smaller converters involved in control computers with a supply voltage of 14V. These systems typically integrate microcontrollers and peripheral circuits.

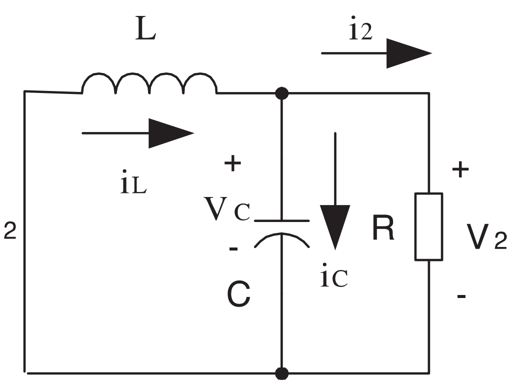
Buck Converter







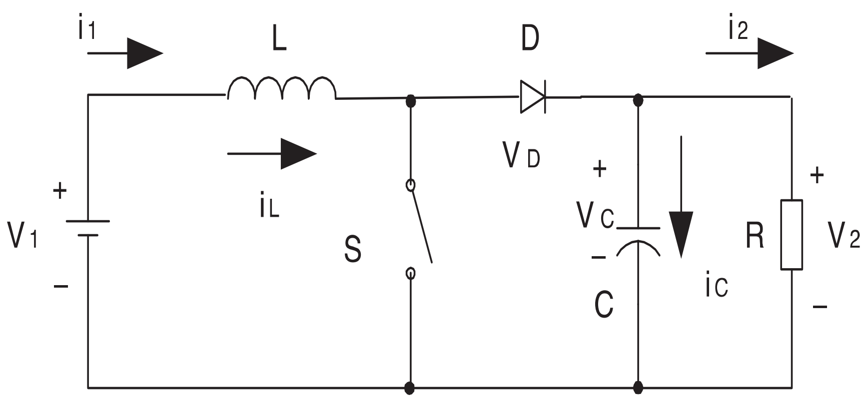
(b) Switch-on

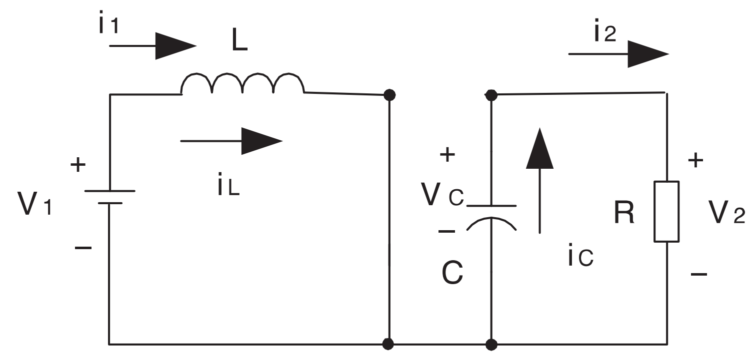


(c) Switch-off

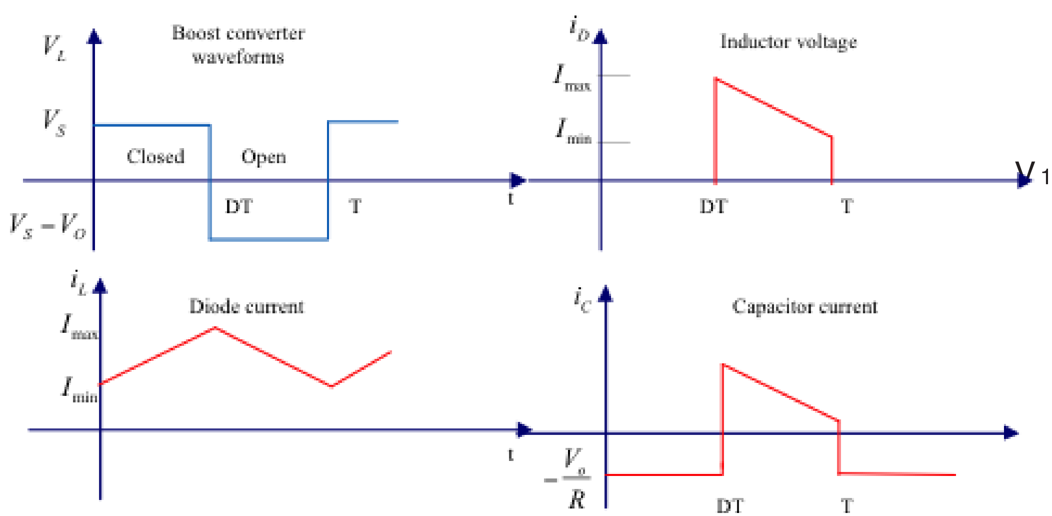
$$V_o = V_s D$$

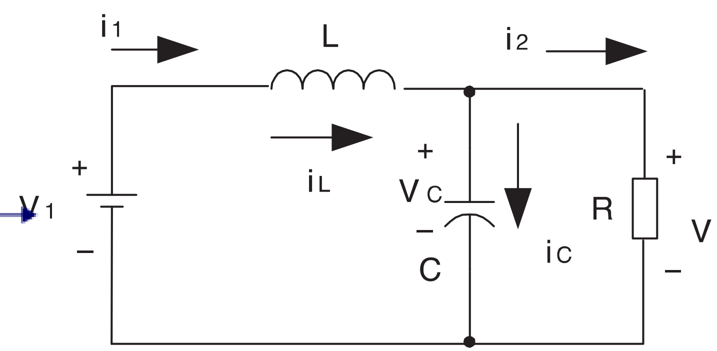
Boost Converter





(b) Switch on

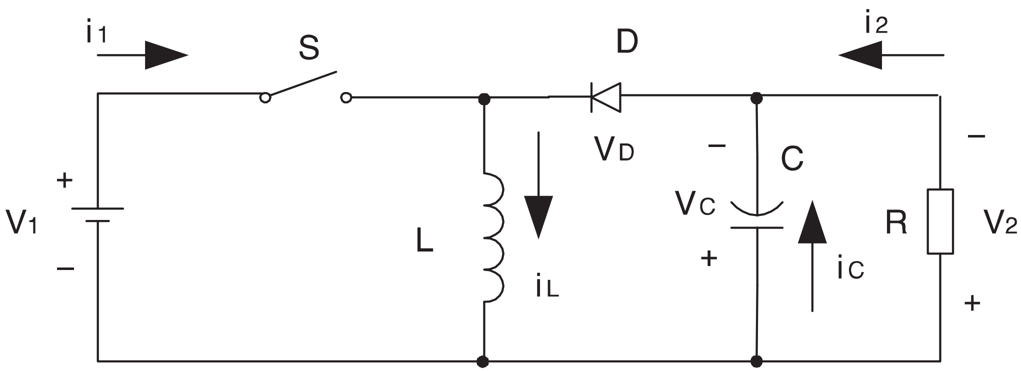


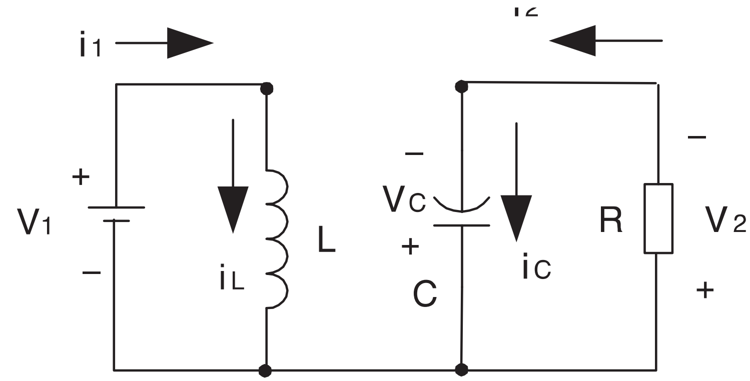


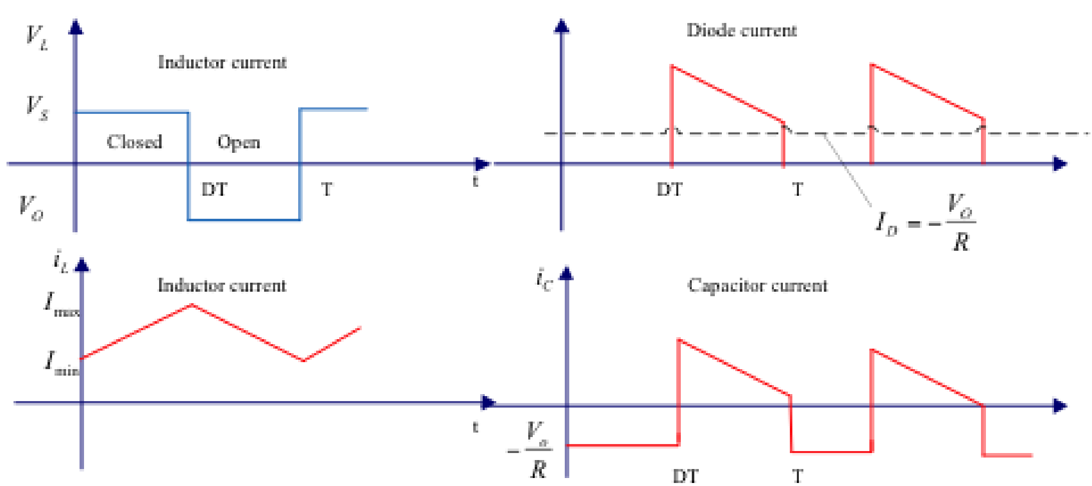
(c) Switch off

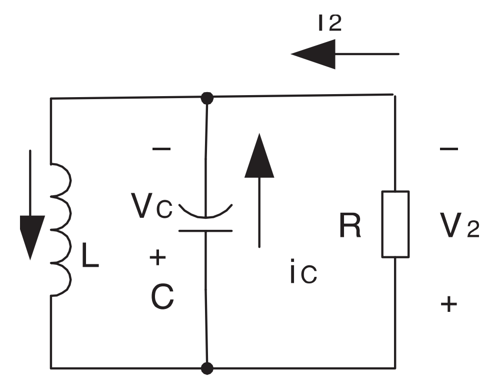
$$V_O = \frac{V_S}{1 - D}$$

Buck-Boost Converter







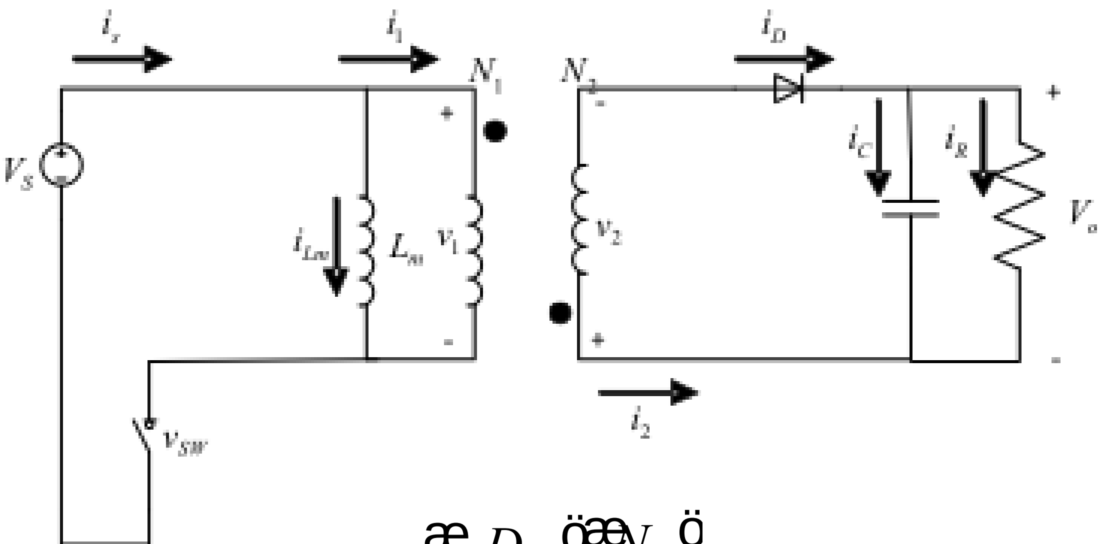


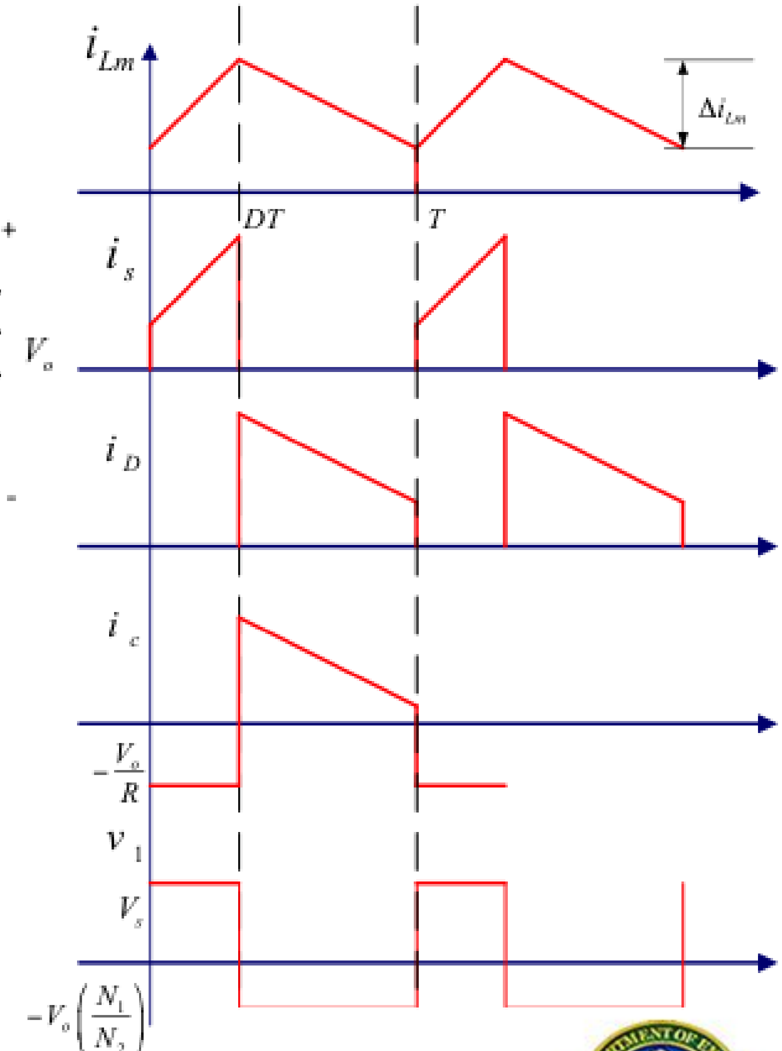
(c) Switch off

$$V_o = -V_s\left(\frac{D}{1-D}\right)$$

$$L_{\min} = \frac{(1-D)^2 R}{2f}$$

Flyback Converter





$$V_o = V_s\left(\frac{D}{1-D}\right)\left(\frac{N_2}{N_1}\right)$$

$$(L_m)_{\min} = \frac{(1-D)^2}{2f}$$

$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf}$$

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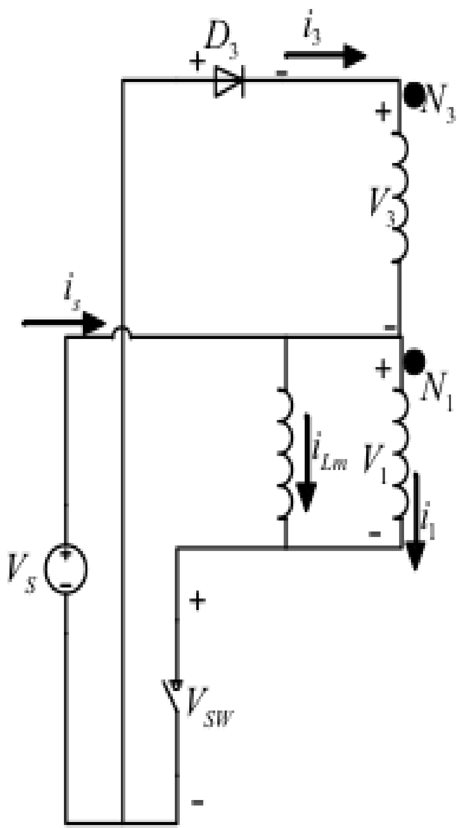
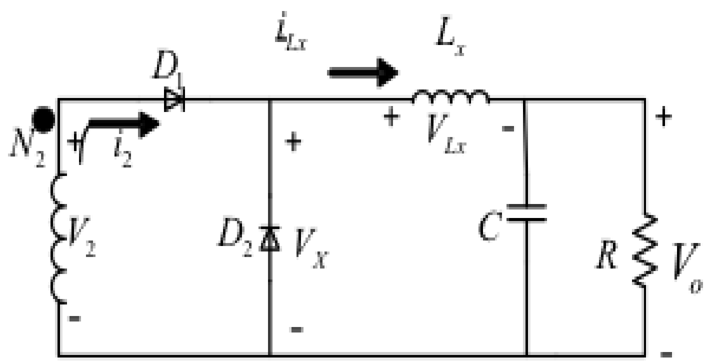
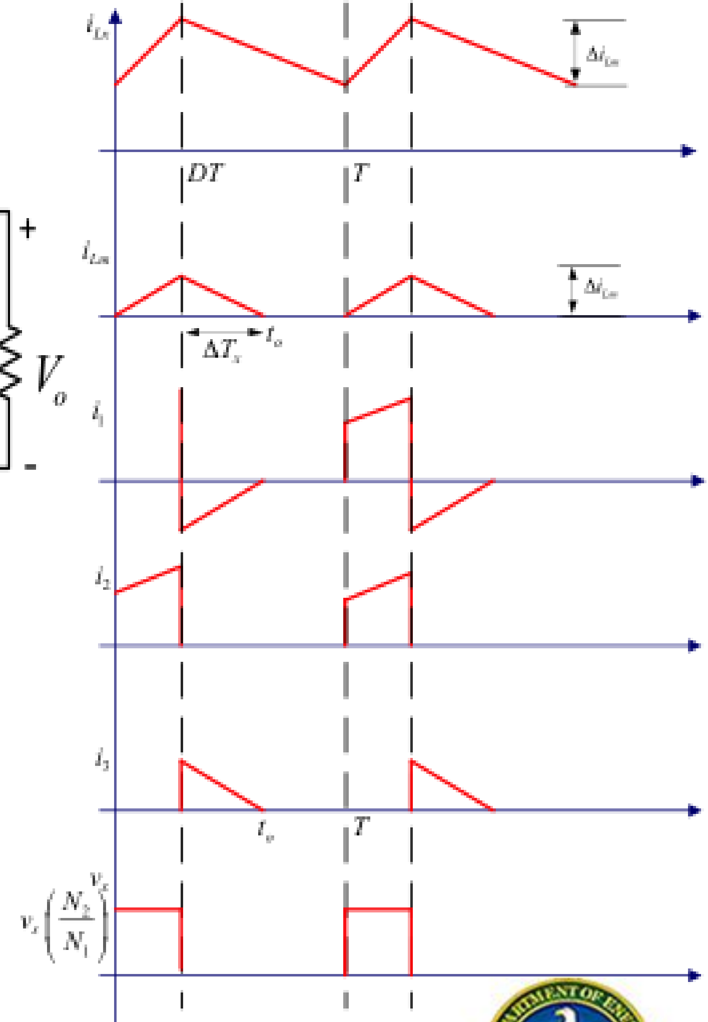
Forward Converter





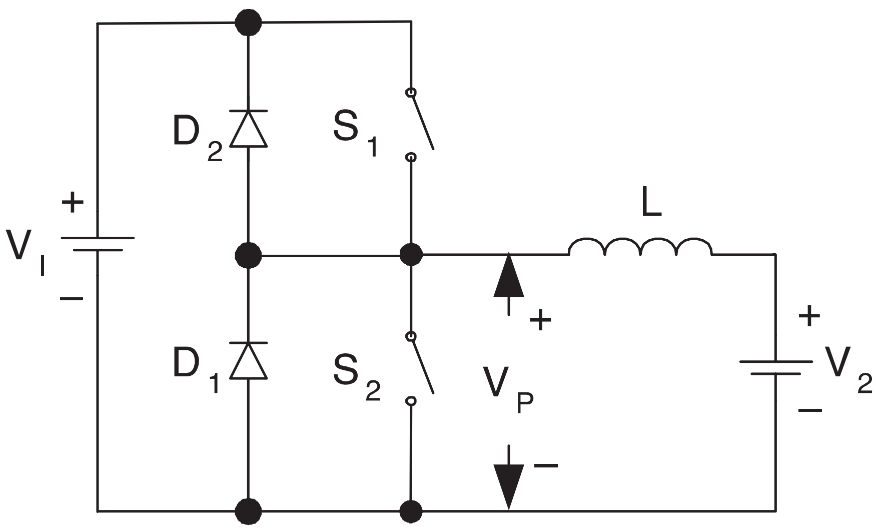


$$V_o = V_s D \left(\frac{N_2}{N_1} \right)$$

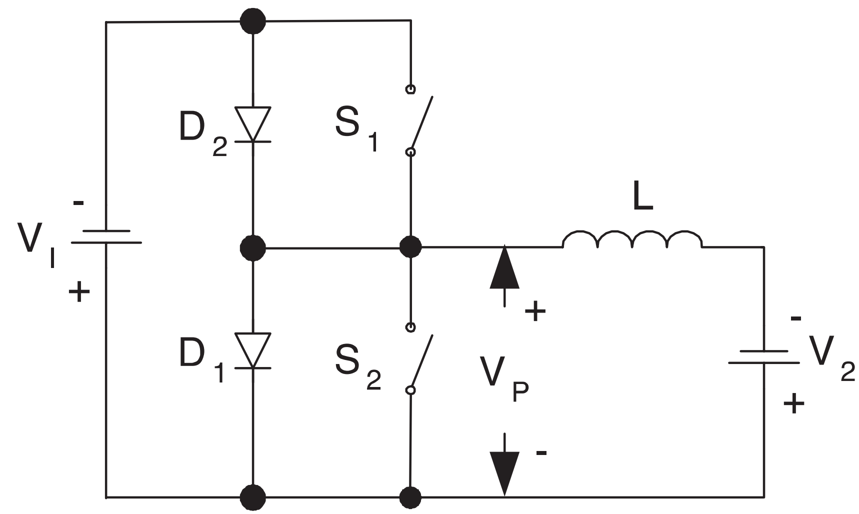
Take Away Points: DC/DC Converters

- DC/DC Converters play a critical role in the energy conversion to and from the battery in an Electric Vehicle.
- Increasing the frequency of switching can directly result in reduction in the size of the passive elements.
- Batteries and converters operating at higher voltages tend to be smaller than ones operating at higher current.

Two Quadrant Converter



1st and 2nd Quadrant



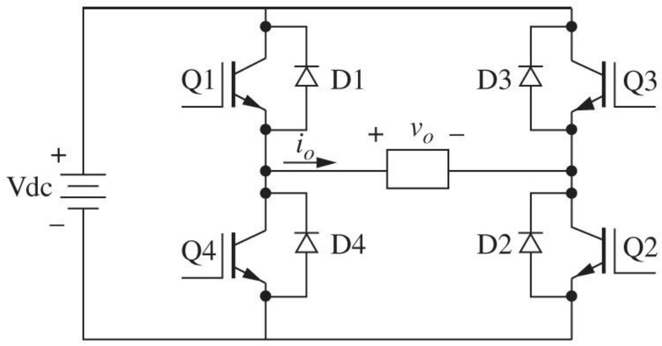
3rd and 4th Quadrant

$$V_2 = \begin{cases} kV_1 & QI\_operation \\ (1-k)V_1 & QII\_operation \end{cases}$$

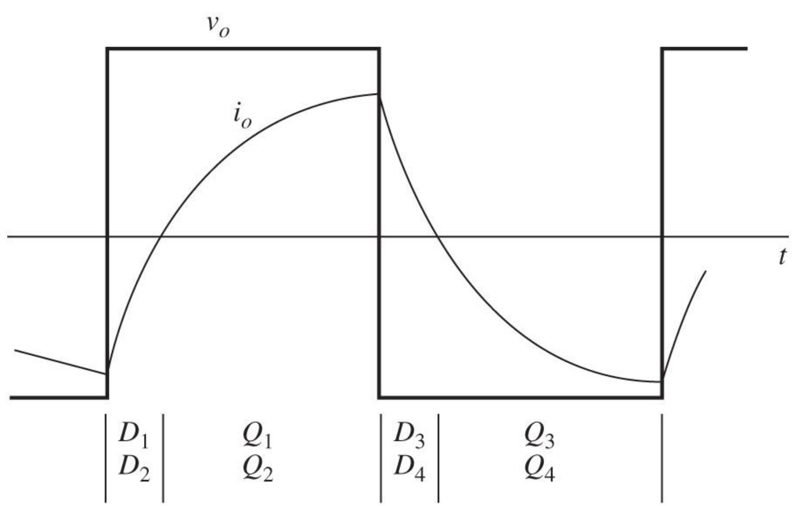
$$V_2 = \begin{cases} kV_1 & QIII\_operation \\ (1-k)V_1 & QIV\_operation \end{cases}$$

k is the conduction duty cycle $k = t_{on}/T$.

Converters: Full Bridge DC/AC Inverter



(*a*)



(*b*)

Switches Closed	**Output Voltage, v_o**
Q_1 and Q_2	**$+V_{dc}$**
Q_3 and Q_4	**$-V_{dc}$**
Q_1 and Q_3	**0**
Q_2 and Q_4	**0**

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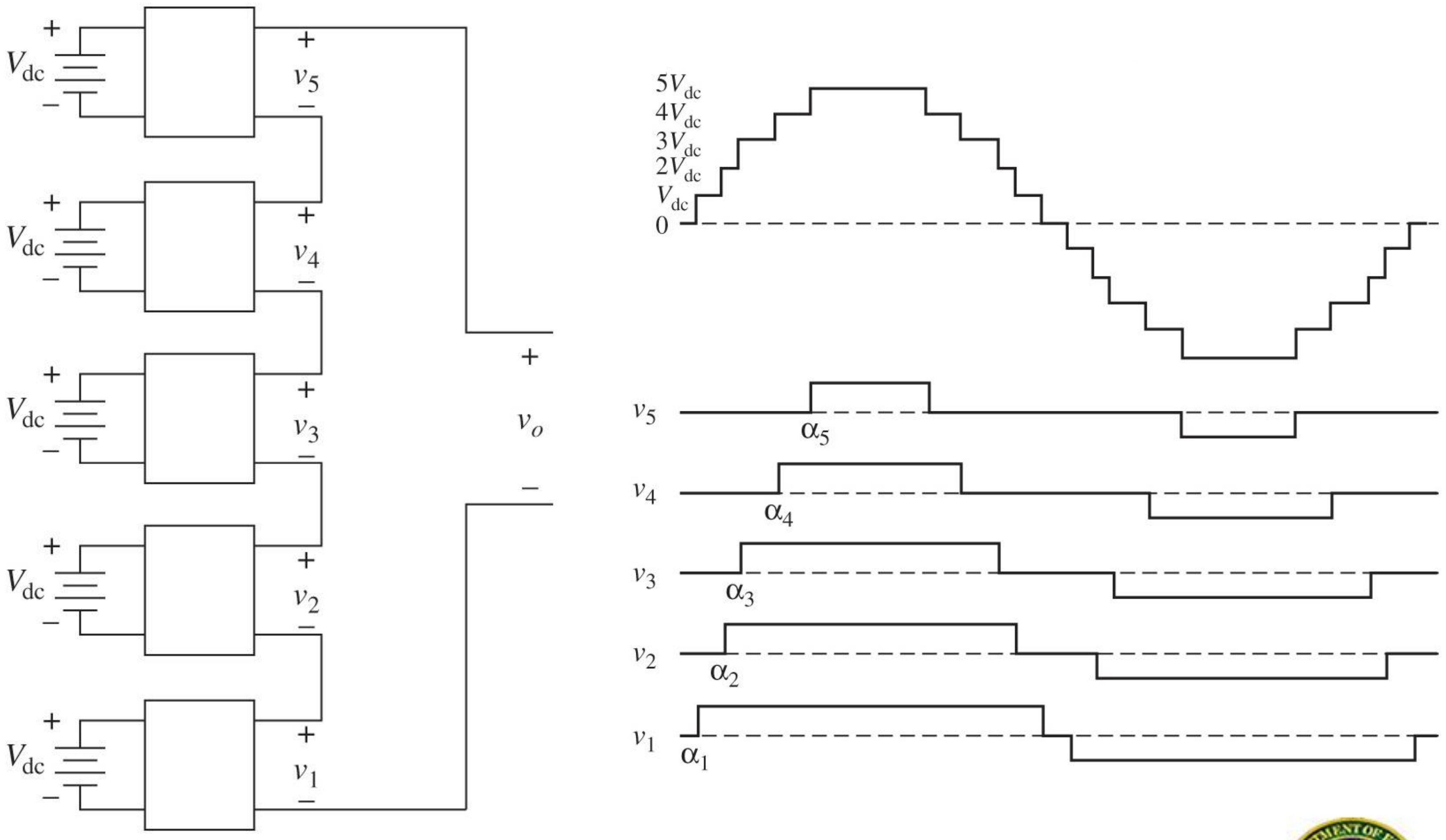
Multi-level Converter



Design of Power Electronic Circuits

- **Design and component selection**
  - Circuit and controller design
  - Component selection
  - Selection of switching frequency
  - Loss estimation

- **Selection of passive circuit components**
  - Design of magnetic elements including inductors and transformers
  - Selection of capacitors

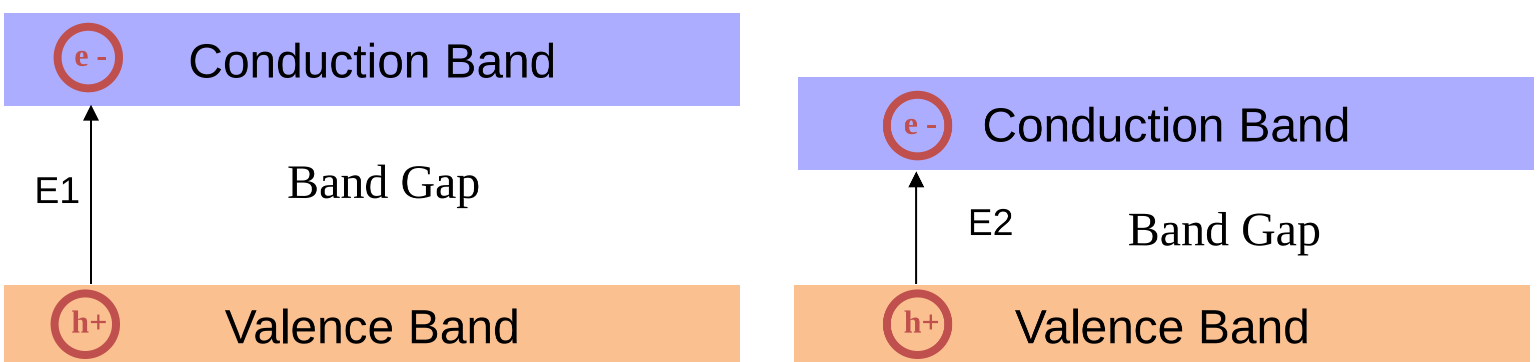
- **EMC analysis:**
  - Analyzing electromagnetic emissions
  - Determination of witching transients,
  - Optimal circuit layout to minimize parasitics

- **Mechanical and thermal design:**
  - Loss modeling
  - Thermal management and packaging

Emerging Technologies: Wide Bandgap Devices

What’s a WBG device?

- Wide Bandgap (WBG) material has a higher energy bandgap than Si, around 3 times of Si, which means higher energy is needed to excite electrons from valence band into conduction band.
- This property leads to (SiC) devices with higher thermal and radiation durability.
- The critical junction temperature of Si devices which makes it uncontrollable is around 150°C while it is around 900°C for SiC devices.



E1 > E2

Which WBG Device?

- Si devices are limited to operation at junction temperatures lower than 200 ºC and are not suitable for very high frequency operation
- SiC and GaN offer the potential to overcome both the temperature, frequency and power management limitations of Si
- GaN & SiC process technologies are more mature. Currently, SiC is considered to have the best trade-off between properties and commercial maturity.
- GaN can offer better HF and HV performances, but the lack of good quality large area substrates is a disadvantage for vertical devices
- GaN presents a lower thermal conductivity than SiC GaN allows forming 2DEG heterojunctions (InAlGaN alloys) grown on SiC or Si substrates.
- So it is essentially a race between SiC and GaN in terms of performance and cost.

Advancements and Challenges in WBG Devices

- SiC and GaN based switches can have several benefits over Si-based devices:
  - Much smaller switching losses, leading to higher efficiency
  - Able to operate at higher temperatures without much change in electrical properties, leading to better reliability
  - Smaller heat sink because of lower losses
  - High frequency of operation allows smaller filters, which leads to light and compact packaging

- Challenges in SiC commercialization
  - Elimination of defects (discoloration and dislocation issues)
  - This leads to poor reverse blocking performance
  - Cost

1200V SiC Switch Comparison

Device type	Silicon IGBT	SiC MOSFET	SiC JFET (norm-off)	SiC JFET (norm-on)	SiC BJT
Best Effective R_{sp} ($m\Omega cm^2$)	20	5-8	4	3.2	2.3
Positive tempco across temperature	Yes at high current	no	yes	yes	yes
normally-off	yes	yes	yes	no	yes
DC drive current	no	no	yes	no	yes
Body diode included in the device	no	Yes, but low performance	no	no	no
Oxide reliability needed	Yes, but no issue on Si	yes	no	no	no
Normalized Switching loss 800 V, 20 A	2 mJ	850 µJ	470uJ	470 µJ	340 µJ
Ruggedness	Good	Very good	Good	Very good	Very good

Source: Fairchild Semiconductors

Physical Properties of SiC and Si

Property	Si	3C-SiC	6H-SiC	4H-SiC
Bandgap, E_g (eV at 300K)	1.12	2.4	3.0	3.2
Critical electric field, E_C (V/cm)	2.5x105	2x106	2.5x106	2.2x106
Thermal conductivity, λ (W/cmK at 300K)	1.5	3.4	3.4	3.4
Saturated electron drift velocity, vsat (cm/s)	1x107	2.5x107	2x107	2x107
Electron Mobility, μ_n (cm2/V•s)	1350	1000	500	950
Hole Mobility, μ_p (cm2/V•s)	480	40	80	120
Dielectric constant, εr	11.9	9.7	10	10

Ref: M. Östling, R. Ghandi and C. –M. Zetterling , "SiC power devices – present status, applications and future perspective", Proceedings of the 23rd International Symposium on Power Semiconductor Devices & IC's May 23-26, 2011 San Diego, CA

Properties of SiC Vs. Si

- Wide band gap (3x Si)
- High breakdown field (10x Si)
- High thermal conductivity (3x Si)
- High temperature stability

Silicon Carbide and Silicon Devices

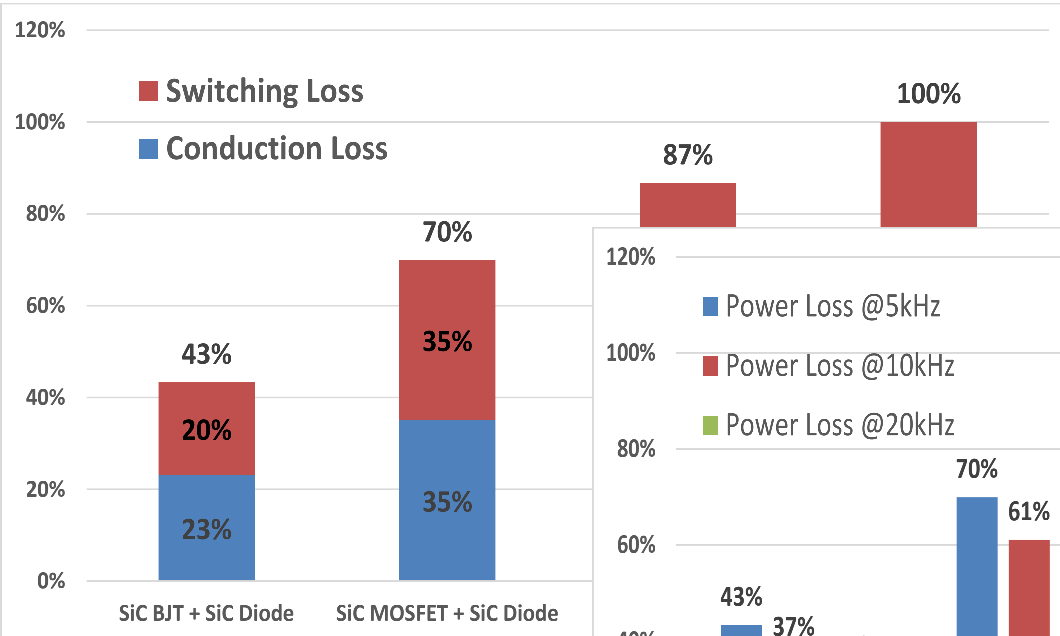


Figure: Power loss evaluation of SiC and

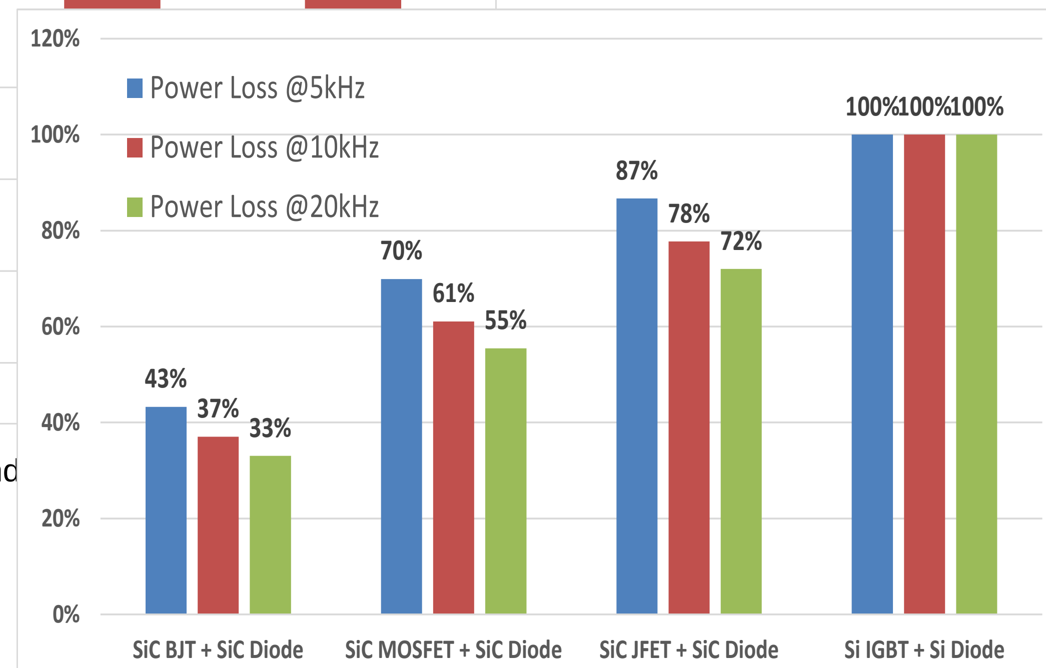


Figure: Power loss of SiC and Si devices with increasing switching frequency.

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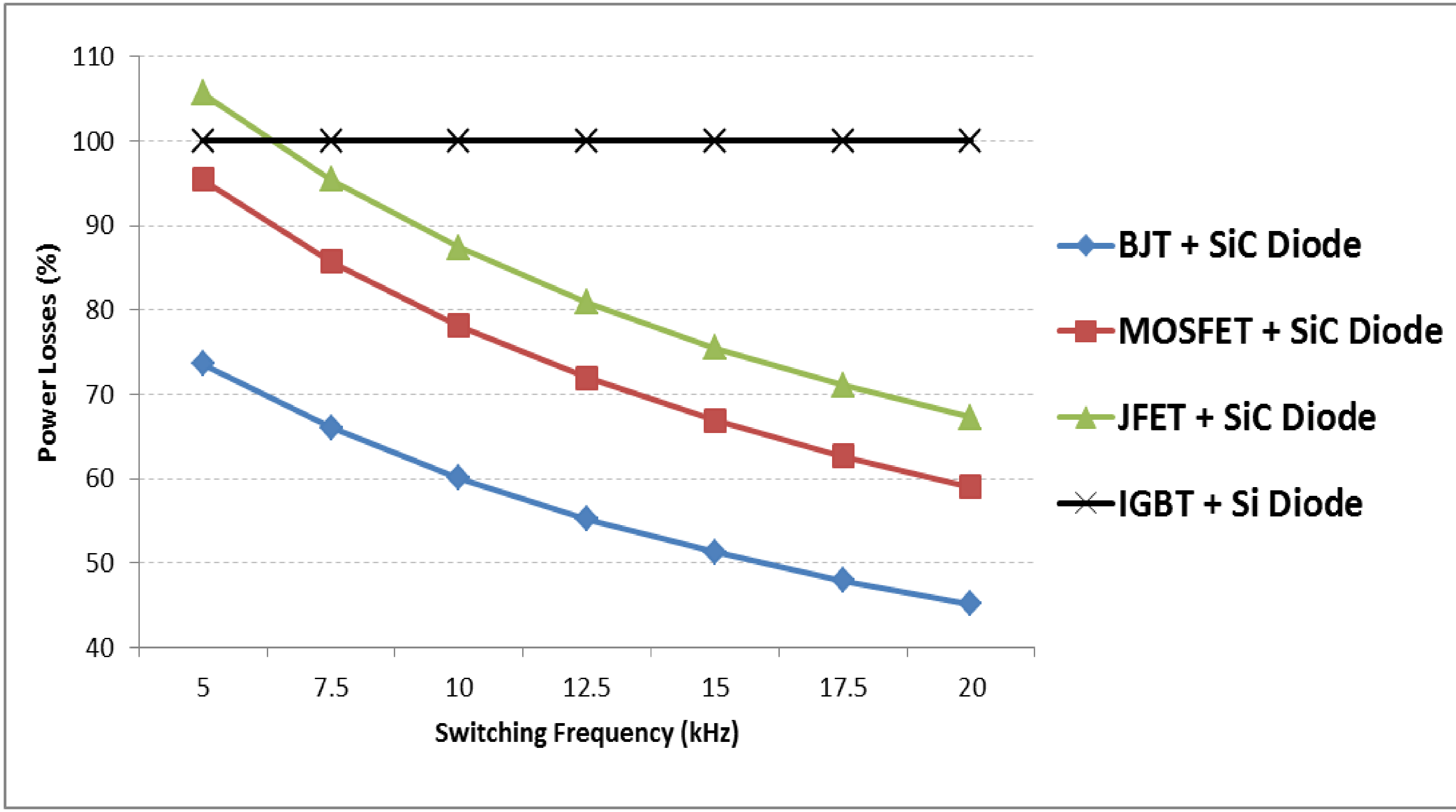
Silicon Carbide and Silicon Devices



Market Overview

- Several manufacturers: BJT from Fairchild and GeneSiC (SJT), JFET from Infineon and MOSFET from Cree, Rohm and ST.

- For the voltage rating, most of the announced devices are 1200V, which meet the requirements for 600V DC bus applications in EVs.

- Fairchild and GeneSiC have announced their high temperature SiC BJTs with maximum junction temperature of 250°- could be an ideal choice for high temperature application such as traction power converters.

- Besides the discrete package transistors, manufactures such as Cree and Rohm, have built up power modules with SiC transistors and SiC Schottky diodes for higher power applications.

Questions to be Addressed…

SiC Devices:

- EMI and parasitic parameters
- Implementation of high temperature converter (not just the switch)
- Cost and reliability

GaN Devices:

- Normally-on
- “Current collapse” due to interface traps
- Cost and reliability
- Lateral structure with limited current capability

- 2-3% efficiency improvement at 8-10X cost of Si
  - ✓ Material cost
  - ✓ Fabrication cost
- Reliability (gate oxide, current collapse, etc.)
- Other practical barriers

Challenges Ahead in WBG

- Develop advanced processes for growing other WBG materials to be used in power electronic devices
- High-voltage WBG semiconductor device design and development
- Develop alternate power electronic structures and assemblies
- Power electronics packaging and thermal design for use in harsh environments
- Reliability Testing

Cooling Systems

Development of Thermal Control Technologies

Key barriers:

- Inadequate techniques for dissipating high heat fluxes while limiting the operation of silicon-based components to a temperature < 125 C.
- Current components are generally both bulky and heavy --> need additional structural support and more parasitic power.
- Material and processing technologies remain too costly for use

Expected benefits of good thermal control:

- Higher power densities,
- Smaller volumes and weights
- Increased reliability for the drivetrain components.
- Lower costs

2020 FreedomCAR Goals

- Current approach towards cooling HEV inverters uses a separate cooling loop with water ethylene glycol coolant at approximately 70°C.
- Used in hybrid electric vehicles (HEVs) such as the Toyota Prius and Ford Escape.
- Cost target for FreedomCAR program for electric traction drive is $8/kW of peak power based on a 3-year payback on the incremental vehicle cost.
- Total traction system (power electronics and electric machines) cost target for a 55kW system becomes $440.
- To help reduce the costs of the system, on-board coolants are needed.

Propulsion System Targets for 2020

FreedomCAR Goals	
Peak Power	55 kW for 18 seconds
Continuous Power	30 kW
Lifetime	>15 years (150,000 miles)
Technical Targets based on maximum coolant temperature of 105 C	
Cost	<$8/kW peak
Specific Power at peak load	>1.4 kW/kg
Volumetric Power Density	>4.0 kW/liter
Efficiency (10 to 100% speed, 20% rated torque)	94%

Selecting a Thermal Management Solution

Direct Versus Indirect Liquid Cooling

- Nearly all existing hybrid vehicle cooling work centers on *indirect liquid cooling* of the chip
- Several layers of materials separate the chip from the liquid coolant. Corresponding resistance creates a relatively large temperature gradient when high heat fluxes are dissipated.

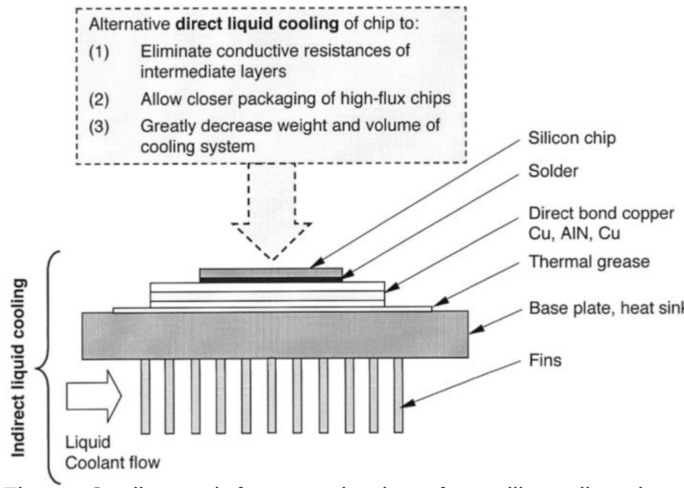
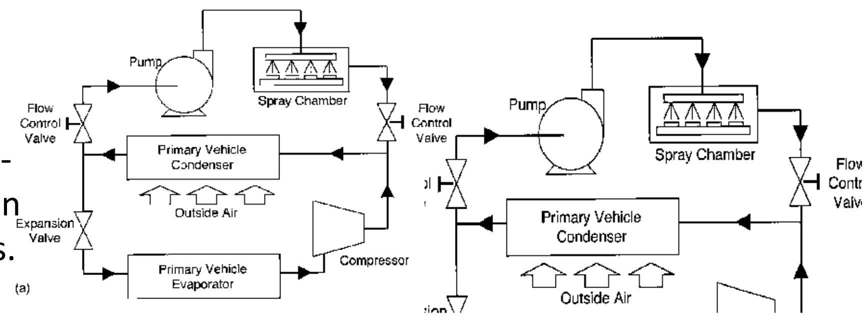


Figure: Cooling path for removing heat from silicon die using indirect cooling with water/ethylene glycol, and alternative direct liquid cooling.

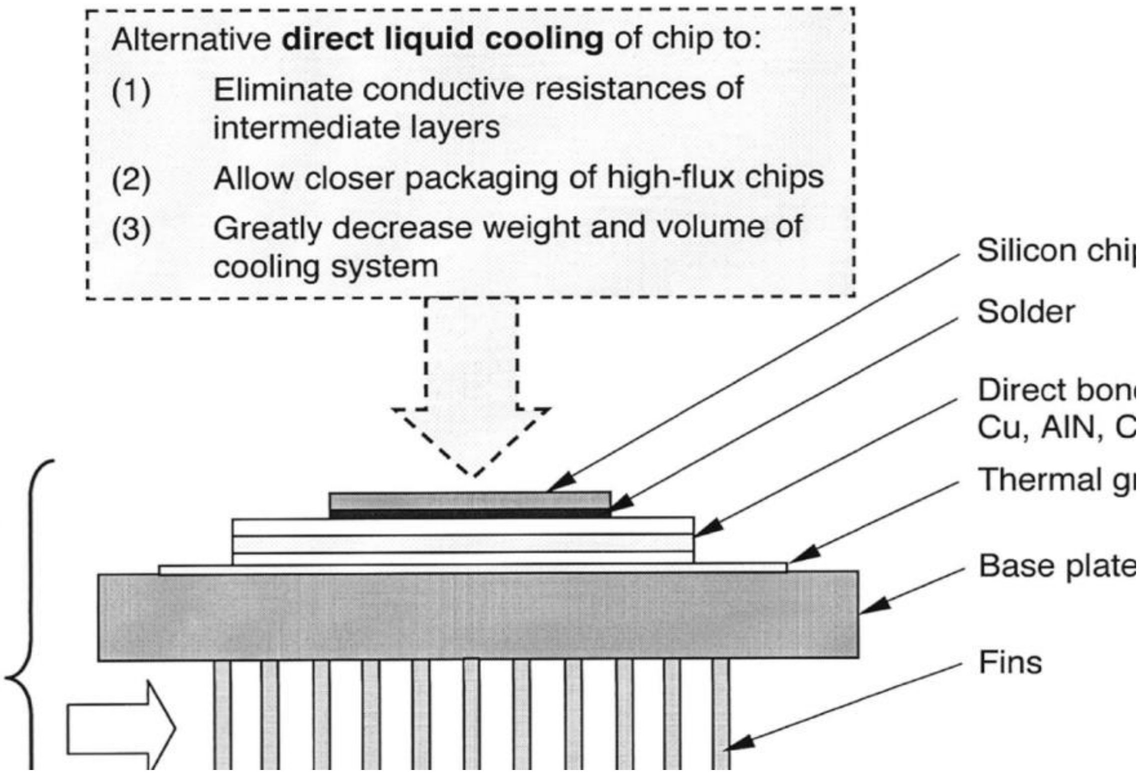
Spray Cooling

- Two possible cooling loop configurations-
  - Modifying the vehicle's refrigeration loop with a pump-assisted sub-loop containing a spray-cooling chamber in which the heat is removed from the vehicle electronics.
  - Electronics are cooled by a separate loop using an appropriate coolant.



Ref: Mudawar et al, "Two-Phase Spray Cooling of Hybrid Vehicle Electronics", IEEE Transactions on Components and Packaging Technologies

Fluids used for Cooling



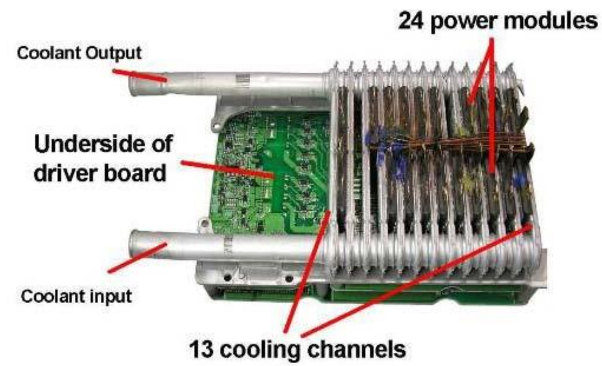


Figure: Capabilities of existing cooling technologies using various fluids and operating pressures.

Ref: Mudawar et al, "Two-Phase Spray Cooling of Hybrid Vehicle Electronics", IEEE Transactions on Components and Packaging Technologies

Coolant Selection

- ***Dielectric strength:*** Highest voltage that can be sustained across a layer of the fluid before fluid breakdown or arcing takes place.
- ***Dielectric constant*:** Electrostatic energy that can be stored per unit volume of fluid when a unit voltage is applied.
- ***Flammability*:** Susceptibility of the fluid to ignite, either spontaneously or as a result of a spark or open flame.
- ***Auto-ignition temperature***: Temperature at which fluid would self-ignite.
- ***Lower explosive limit*:** Concentration of fluid for a given volume of air that renders a mixture flammable or explosive.
- ***Ozone depletion potential*:** Relative index indicating the extent to which the fluid may cause ozone depletion.
- ***Global warming potential*:** Indicates how much a given mass of the refrigerant contributes to global warming over a 100-year period compared with the same mass of CO.

R&D and Commercialization Challenges for EV Power Electronics

Challenges in Power Electronics

- **Cost**
  - Power module
  - Passive components
- **Volume and mass reductions are needed**
  - Driven by passive devices
- **Packaging and Advanced materials required**
  - Higher temperature capability
  - Increase thermal conductivity
- **Reliability**
  - Wire bonds, die and substrate attach, solders, & connectors
  - Substrates and epoxies
- **Thermal Management**
  - Liquid cooling to air
  - Single sided or double sided
- **Efficiency**
  - Idle or quiescent loads

EV Targets

Table: Batteries and Energy Storage 2022 Targets (EV Everywhere 5-year payback analysis)

		Current Status	PHEV40	AEV100	AEV300
System Cost	$/kw	20	5	14	4
Motor Specific Power	kW/kg	1.2	1.9	1.3	1.3
Power Electronics Specific Power	kW/kg	10.5	16	12	16.7
System Peak Efficiency	%	90	97	91	98

Source: DOE, EV Everywhere A Grand Challenge in Plug-In Electric Vehicles

Targets for On-Board Charging

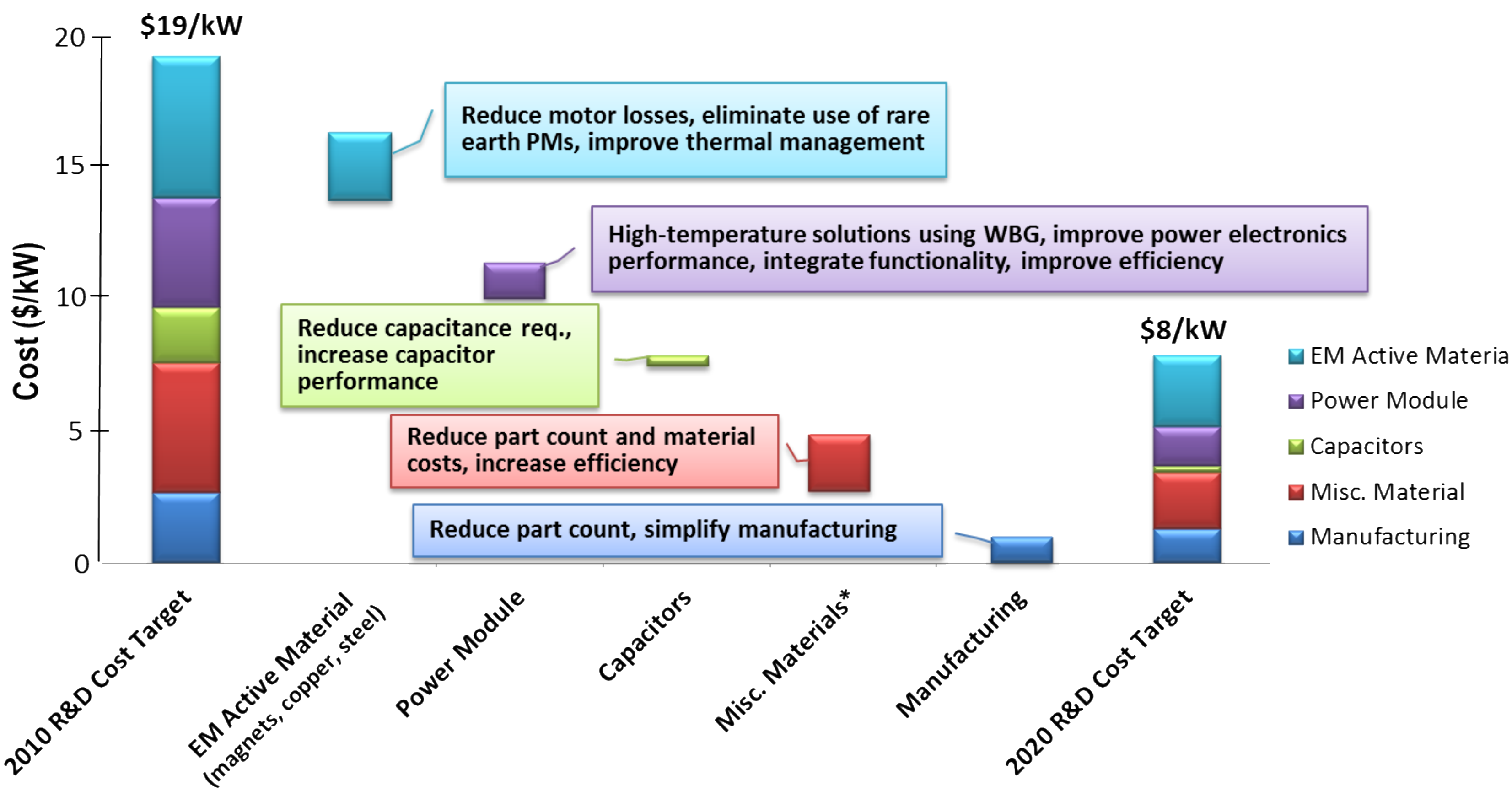
Key Challenges:

- Cost
- Weight and volume
- Traction drive and vehicle-level integration
- Integrated functionality
- Long-term solutions for fast charging and wireless power transfer

3.3 kW Charger	2010	2015	2022
Cost	\$900 - \$1,000	\$600	\$330
Size	6-9 liters	4.0 liters	3.5 liters
Weight	9-12 kg	4.0 kg	3.5 kg
Efficiency	90% – 92%	93%	94%

Source: DOE, EV Everywhere Grand Challenge

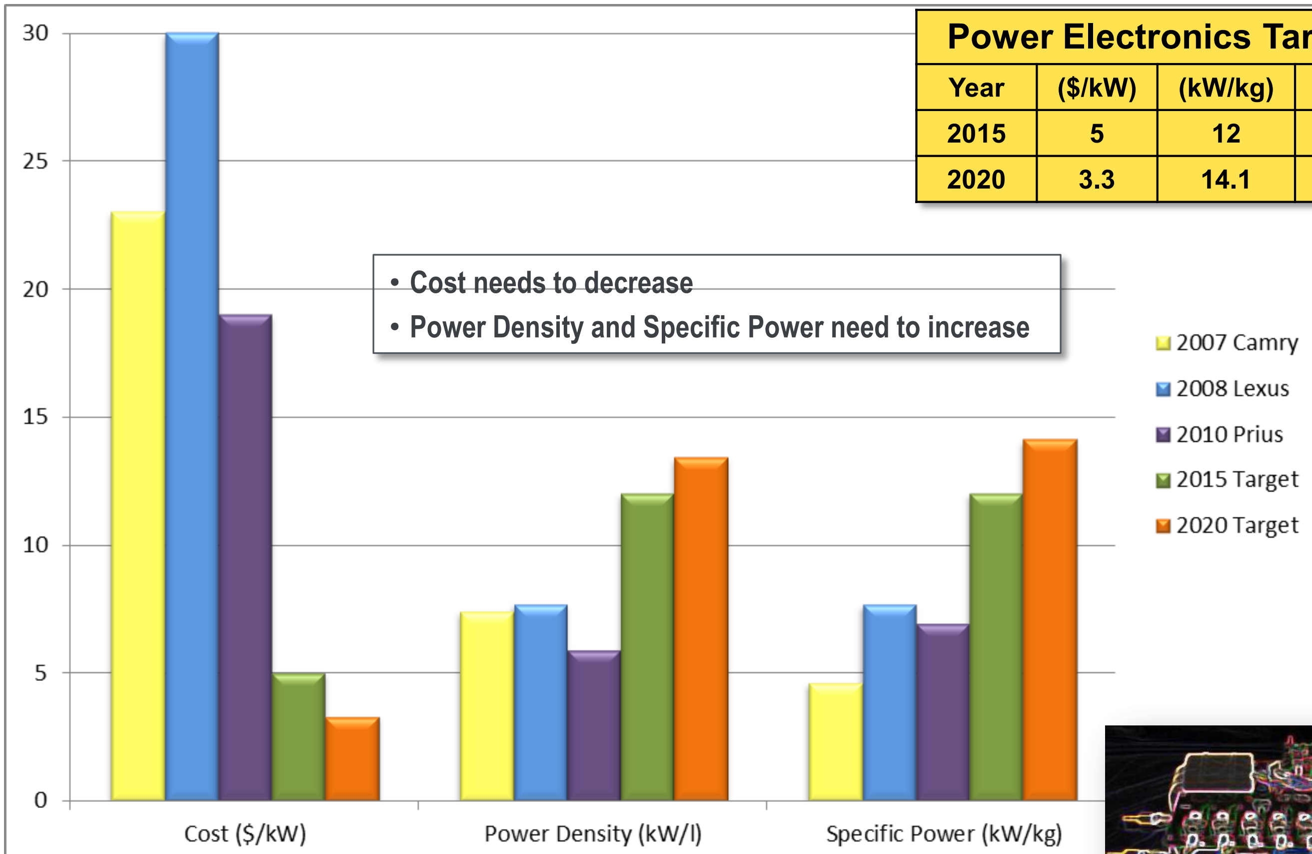
System-Level Targets



*** Inverter: cold plate, drive boards, thermal interface material, bus bar, current sensors, housing, control board, etc.**
Motor: bearings, housing, sensors, wire varnish and insulation, potting materials, shaft, etc.

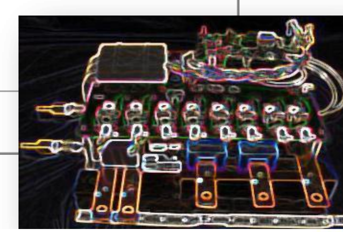
Source: DOE, EV Everywhere Grand Challenge

Targets for Power Electronics in Traction



Power Electronics Targets

Year	($/kW)	(kW/kg)	(kW/l)
2015	5	12	12
2020	3.3	14.1	13.4



Source: DOE, EV Everywhere Grand Challenge

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Summary & Conclusions

- Hybrid Electric Vehicles, Plug-in Hybrid Vehicles and Electric Vehicles play a major role towards the nation's energy independence
- Although several advancements have been made in enabling technologies and architectures, much needs to be done to attain wider acceptance
- Cost and (all-electric) range are key issues that hinder wider acceptance of Electric Vehicles
- In order to derive optimal performance from an EV, advancements are needed in each area, including power electronics, motor drives and energy storage
- *It is an exciting time to be working in this area where every improvement and every innovation can make a difference!!*

Questions?

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